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THE ANTIPROTON-NUCLEUS INTERACTION

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ABSTRACT

Several facets of antinucleon-nucleus interactions are explored. The topics treated are: coherent interactions, production of unsual states and particles in the nuclear medium, and the creation of extreme states of matter by antimatter annihilation. It is found that temperatures of the magnitude necessary to achieve the predicted quark-gluon phase transition are obtained.

THE COHERENT INTERACTION OF ANTINUCLEONS WITH NUCLEI

In order to relate the $\bar{p}$-nucleon properties to $\bar{p}$-nucleus characteristics we wish to construct a model of $\bar{N}$'s interacting with nuclei from the $\bar{N}N$ interaction. The most obvious way to do this is by using the multiple scattering formalism developed in recent years[1]. I summarize very briefly here the basic formula for the representation of a $\bar{p}$-nucleus potential in terms of two-body data. To develop such an expression one must realize that the projectile-nucleon interaction in the nucleus may be very different from that in free space. It is, in fact, altered in several ways but the governing notion is that the nucleon in the nucleus is interacting with other nucleons at the same time as with the projectile. Hence the spectrum of intermediate states is restricted in several ways. One may separate the Hamiltonian in the Green's function into a projectile-nucleon part and a nucleon-nucleus part by using 1) the Watson-KMT optical model expansion, 2) the assumption that the projectile-nucleon interaction is of short range compared with the nucleon-nucleus range and 3) an independent-particle shell model for the nucleon motion in the nucleus. This procedure leads to the following expression for the $\bar{p}$-nucleus potential.

$$\langle\vec{k}'|V(E)|\vec{k}\rangle = \sum_{AA'} \int d\vec{q}'\, d\vec{q}\, \phi_A(\vec{q}')\phi_{A'}(\vec{q}'+\vec{k}')$$

$$\times \langle -\tfrac{1}{2}\vec{q}'+\tfrac{1}{2}\vec{k}'|t(E+E_A-E_{A'})|-\tfrac{1}{2}\vec{q}+\tfrac{1}{2}\vec{k}\rangle\, \phi_{A'}(\vec{q}+\vec{k})\phi_A(\vec{q})$$

The labels A and A′ stand for the quantum numbers of the single particle nuclear states and A′ is summed over all of the intermediate single particle states, A over the occupied states in the target. Pauli blocking is included by replacing the t-matrix

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(equivalent to the off-shell amplitude) by the potential if the index A' represents one of the filled target states. Thus one needs a consistent potential and t-matrix which represent the interaction in the $\bar{N}N$ system. The ones used in the results presented here are due to the Paris group (Côté et al.[2]).

The physical effects reflected in this nuclear potential are:

1) There is a discrete spectrum of energies, due to the finite size of the system. The t-matrix must be known up to energies which are approximately twice that of the beam energy, and in principle, to energies down to $-\infty$. In practice the negative energies contribute little to the sum. (We have assumed, however, that any "bound states" of the two body system that might exist are unimportant).

2) The recoil of the nucleon in the nuclear medium is included.

3) The finite size of the $\bar{p}N$ system is seen in two ways. First, the partial waves (higher than s-wave) give a measure of an "on-shell" size. The off-shell form factors also give a size of the system for intermediate scattering of the projectile off-energy-shell. Each of these quantities may be linked to underlying theories of the $\bar{p}N$ system.

4) The Pauli blocking of the nucleons requies that the t-matrix be replaced by the potential for the case that the particular intermediate state in question is not available for the spectrum of the Green function. Since for the antiproton the potential is, in general, larger numerically than the t-matrix, a substantial correction can be expected. Note that, for low energy and hence low momentum, the states corresponding to values of A' which describe the target states are important and one expects that the most important contributions to the $\bar{p}$-nucleus potential come from the $\bar{p}$-nucleon potential. For higher energies the terms involving the t-matrix dominate. How this transition comes about depends on the basic physics input into the calculation, but there are certain general statements which are useful. With the assumption that the $\bar{N}N$ interaction range is small, there is a restriction on which $\bar{p}$-nucleus partial waves can be blocked. Considering a given $\bar{N}N$ partial wave, λ then the highest $\bar{p}$-nucleus wave to be affected is $2L+\lambda$ where L is the highest shell filled in the nucleus. For example, for very low energy $\bar{p}$'s on ^{16}O we expect $\lambda=0$, $L=1$ so that for $\bar{p}$-nucleus waves higher than $\ell = 2$ no Pauli blocking is possible.

To compare with other projectiles we note that for nucleons the blocking is still important above 50 MeV and for pions it is important up to 150 MeV. In the case of the $\bar{p}$ however, the low partial waves, which would be the ones affected, are strongly absorbed in any case (the potential is not real as in the other two cases), and the partial waves dominating the scattering (the peripherial ones) have no blocking due to the angular momentum restrictions mentioned above. For the Pauli effects to be seen in $\bar{p}$-nucleus scattering, very low energies must be used (~ 10 MeV).

Having given a brief introduction to some of the basic physical notions, let us now examine the data and see how they relate to the physics we want to learn.

There have been a number of measurements of $\bar{p}$-atoms made by means of the x-rays emitted in the atomic cascade[3]. In this case the $\bar{p}$ is captured into some high orbit and descends by Auger emission and electromagnetic transitions to arrive at orbits relatively near to the nucleus. Because of the long x-ray lifetime, even a small rate of annihilation on the nucleus causes the nuclear branch to dominate and the $\bar{p}$ to be lost. Thus, from experimental limitations, the lowest orbits cannot be reached. Of course the <u>very</u> lowest orbits, for all but the lightest nuclei, are inside the nucleus and cannot be characterized as an "atomic" system. In

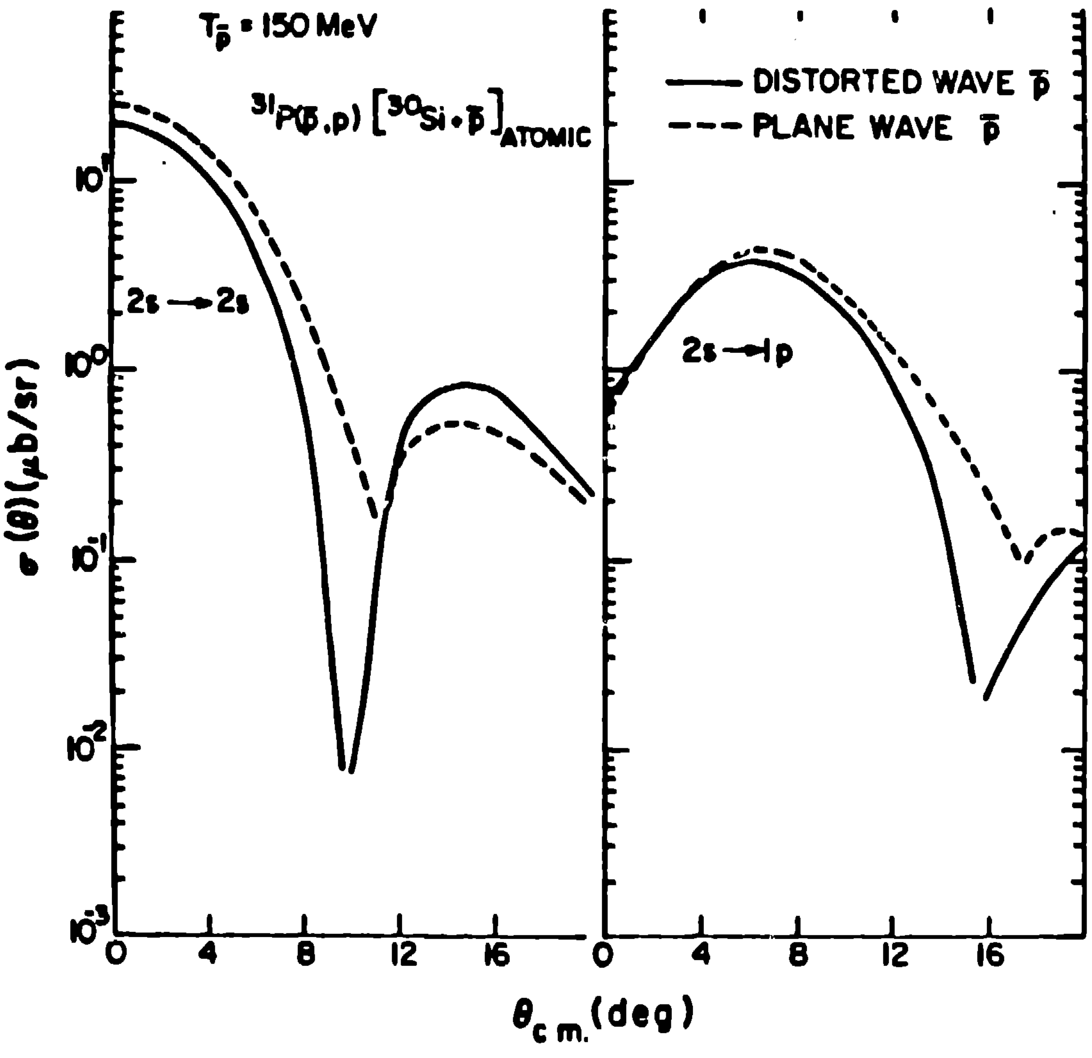

Fig. 1. Differential cross sections for the$(\bar{p},p)$ reaction on ^{31}P.

fact, shifts and widths observed tend to be just on the edge of the blocking boundary. Certainly we would like to examine these lower orbits if we could. The $\bar{p}$-atom data available to date is not of very great accuracy and, due to the rather large errors, we can obtain agreement with the widths easily and the shifts can be fitted within the uncertainties of the potential model used. Since there is new data from LEAR now being analysed of very high quality, we are waiting for these new results before performing a complete study.

For those states which are so near to (or even inside) the nuclear surface that the strong attractive interaction predicted by the G-parity transform of the nucleon-nucleon potential will come into play one expects completely different characteristics than for the atomic states. They should be very deeply bound and very broad, due to the presence of the annihilation channel. An attempt to calculate the properties of such states, and their cross section for population by the $\bar{p}$,p reaction was made by Heiselberg et al.[4] They found deeply bound states with widths of ~ 100 MeV. The reaction calculation that they used was the DWIA, a very dubious choice in this case since the state that they are forming, presumably a state coherent across the nucleus, decays much faster than the transit time of the $\bar{p}$. They also used plane waves for the incoming and outgoing particles, so that even if the above objection were not true one expects that their results are a few orders of magnitude too large.

Nevertheless such states do exist in some sense and in some approximation. Whether they can be observed or not is an open question.

Bill Kaufmann and I recently pointed out[5] that the states so rich in physics between these two extremes are quite accessible. Because of the identity of the mass of the $\bar{p}$ and p, the $\bar{p}$,p reaction can proceed with nearly zero momentum transfer near 0°. This will allow the population of <u>atomic</u> states by knocking a proton out of the <u>nuclear</u> surface. Thus this reaction involves not only the intersection of particle and nuclear physics, but particle, nuclear and atomic physics. The final atomic states populated are those nearest to the nucleus since the overlap with the nuclear wave function is largest in this case. The widths of these states are very large on x-ray standards, but small on nuclear or particle standards (~50 KeV). One should expect to see these narrow structures in $\bar{p}$,p reactions in nuclei but a high resolution beam and spectrometer are required. The most promising target we have found to date is ^{31}P. Our predicted cross sections are shown in Fig. 1. A super-cooled $\bar{p}$ beam would be valuable for this work ($\Delta E < 10$ KeV). The payback in physics is potentially great since one can measure differential cross sections as a function of angle, as well as widths and shifts for these levels in the region where the strong interaction is most important and where the blocking effects are expected to be the strongest. The present LEAR machine can be used for the discovery experiment but even more sophisticated equipment is needed for the detailed studies.

Recently data have become available on $\bar{p}$-nucleus elastic scattering. There are published data[6] on $\bar{p}+^{12}C$ at 46.8 MeV and additional, as yet unpublished data on ^{40}Ca and ^{208}Pb at 46.8 and 179 MeV. In addition, there are slightly poorer resolution data (the low excited states are not separated) from KEK[7] and BNL[8]. From this work, especially the LEAR data, one is able to determine certain properties of the $\bar{p}$-nucleus interaction[9].

It appears that the very strong real potential obtained from the G-parity transform of the proton-nucleus potential does not exist (at least it is not required). This strong potential is not expected from what I said earlier since the G-parity argument applies to the baryon-baryon potential only and, at these energies we expect the nuclear potential to be built from "t", not "v". This is, in some sense, unfortunate since some interesting features of the orbiting states suggested by Auerbach et al.[10] might have given us a handle on the analytic structure of the $\bar{p}$-nucleus S-matrix[11] and thus firm intermediate results with which to compare our theories.

PRODUCTION OF EXOTIC STATES IN THE NUCLEUS

The use of $\bar{p}$ beams to produce exotic mesons in $\bar{p}p$ reactions has been considered for some time. Their use for the production of these particles in nuclei or the production of exotic nuclear states is just now being considered and I shall mention only briefly some of the current topics of interest.

With $\bar{p}$ beams slightly above 3 GeV/c the J/ψ can be produced with no recoil of the nucleus. The charmonium state will propagate through the nucleus and its interaction with nucleons can be inferred by observing deviations from the free, but Fermi averaged, angular distribution.

The possibility of producing baryonium states in the nucleus has been revived by the new evidence for their existence just seen at LEAR[12]. It is too early to design experiments for their scattering from nucleons but the possibilities are clearly there.

The use of the $\bar{p}$, K^- or $\bar{p}$, K^-N reaction for producing $\bar{\Lambda}$'s in nuclei is currently being considered and, if you want more details, you may discuss it with Terry Goldman.

EXTREME NUCLEAR CONDITIONS PRODUCED BY ANTIMATTER-MATTER ANNIHILATION

The idea of depositing large amounts of energy in a small

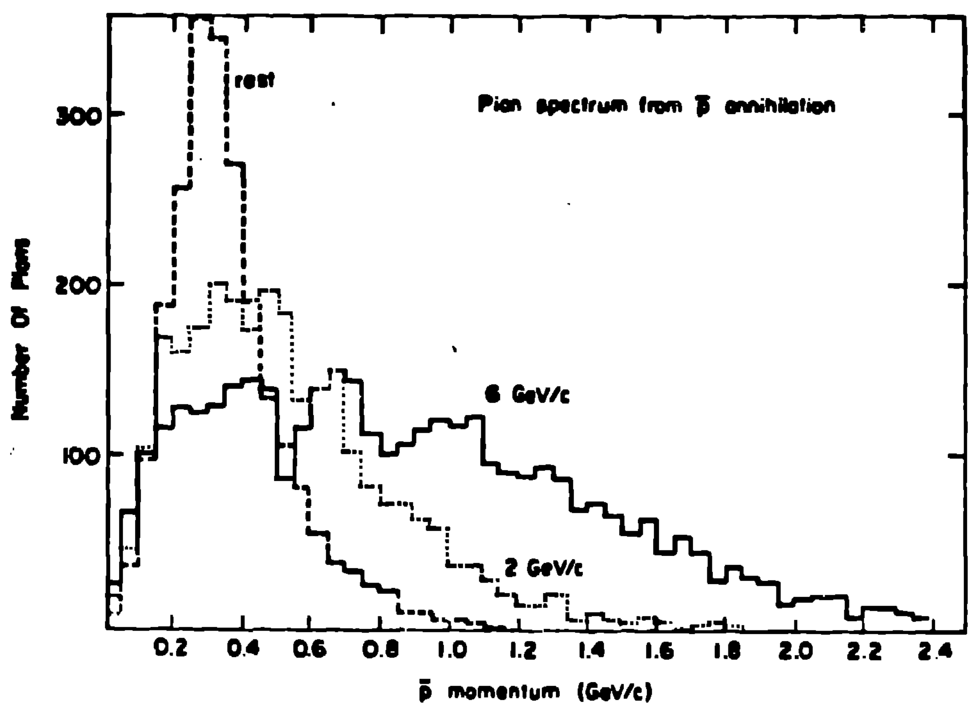

Fig. 2. Pion spectra for three $\bar{p}$ momenta.

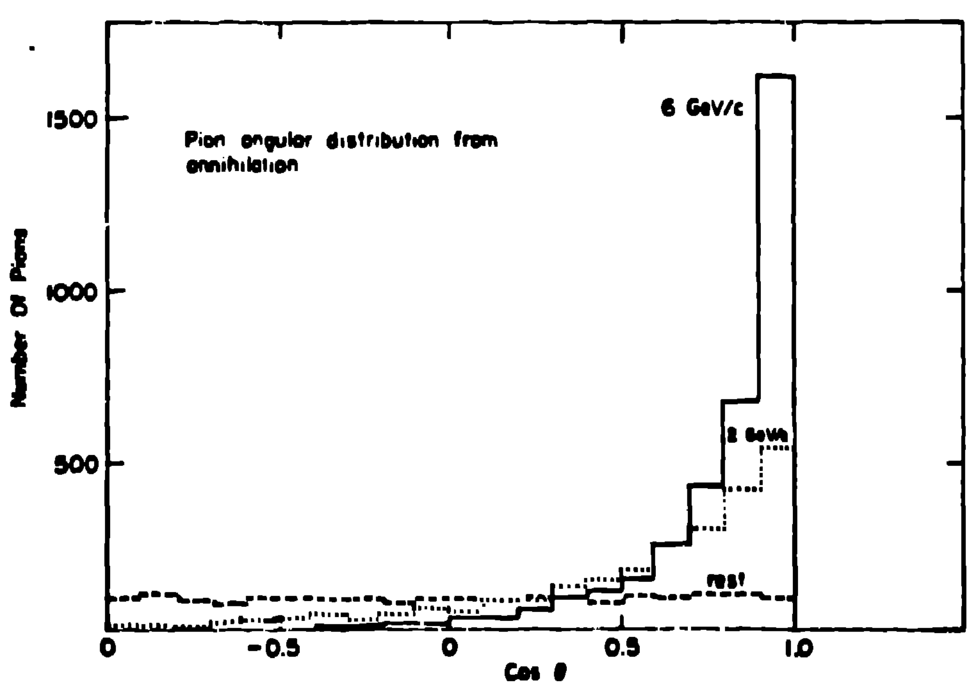

Fig. 3. Pion angular distribution for three $\bar{p}$ momenta.

volume of the nucleus to produce unusual conditions has been discussed before, e.g. ref. 13. Not long ago Dan Strottman calculated the result of a $\bar{p}$ at rest annihilating on the surface of a nucleus[14]. The conditions achieved were not very extreme, in fact, but they are extreme enough to be useful for some studies. Investigations of approximately this type are in progress at LEAR now.

If one increases the momentum of the $\bar{p}$ then the situation differs considerably from the rest condition.

At rest the $\bar{p}p$ system annihilates into approximately 5 pions. These are, of course, isotropic so, radiating from a point on the surface, most of the pions start out in the wrong direction i.e. away from the nucleus. As the energy is increased, the number of pions emitted, in the center-of-mass, increases (slightly), the energy delivered to them increases and they become forward peaked in the laboratory. Figure 2 shows histograms of the pion distributions for three different momenta for the $\bar{p}$. Figure 3 shows the variation of the angular distribution for these same three momenta. At $\bar{p}$ momenta above 6 GeV/c the pion distribution can be considered as a beam of pions - not a very monoenergetic one however.

For the low (or zero) energy case the fact that the pions must cross the nuclear surface also presents a problem. The pions with energies around or below the (3,3) resonanance (a large fraction) tend to suffer large angle scattering and many simply are reflected from the surface, thus depositing only a small fraction of their energy. For $\bar{p}$'s with momenta of the order of 6 GeV/c the mean free path of the $\bar{p}$ has increased to the point that the annihilation occurs within the nuclear material (~.7-1 fm). Thus the pions are <u>created</u> within the nucleus. The large angle scattering of the pions does little harm since they remain within the nucleus in any case.

Realizing that the much greater energy deposition would mean more extreme conditions achieved in the nucleus we (Dan Strottman and myself) set out to find a numerical quantification of this statement[15].

Since the question posed was one of physics, rather than the prediction of a given model, and since the hydrodynamic and intranuclear cascade methods are often opposed in the calculations of heavy ion results, we decided to treat the two models together. He naturally took the hydrodynamic calculations and I, the INC.

The basic conversion of $\bar{p}N$ to pions was done in the same fashion in the two calculations. The energy was distributed among the number of pions $[5.05(S/4m^2)^{1/3}]$ according to phase space in the center-of-mass and then the pions were boosted into the laboratory frame.

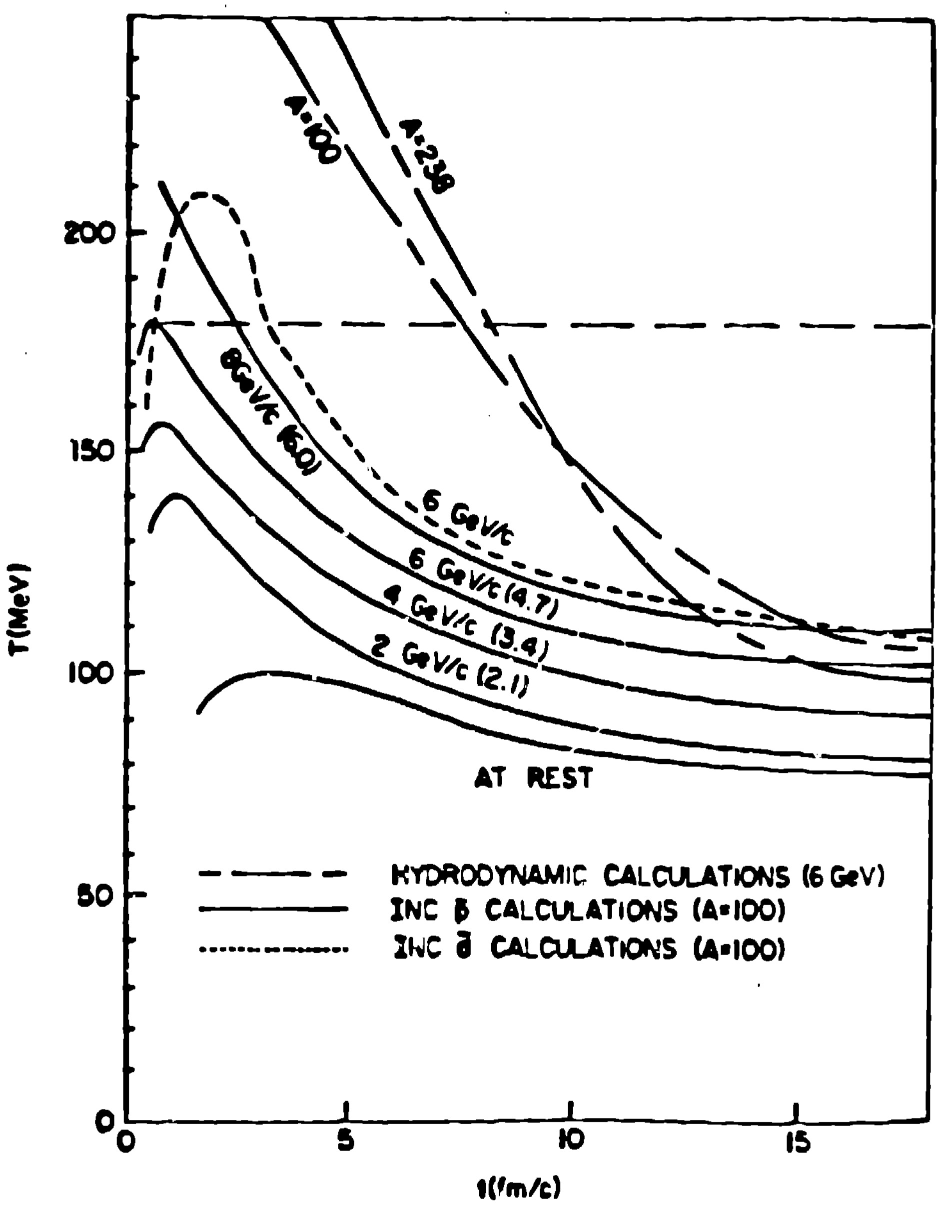

Fig. 4. Temperature achieved for various conditions.

For the hydrodynamic calculations Strottman made a fit to the distribution of energies from this Monte Carlo calculation and then deposited the energy by assuming that (after a hadronization length of γ fm) half of the pions were absorbed after each mean free path. The energy thus deposited was propagated according to the same relativistic hydrodynamic equations used to successfully calculate the properties of heavy ion collisions[16]. He found that the maximum nuclear densities achieved were modest and about the same as for annihilation at rest (~1.8 ρ_o). The extra energy deposited all goes into heating the matter, rather than into compressional energy.

For the INC calculation I was able to use the direct output of the Monte Carlo of the annihilation as input to the main Monte Carlo to follow each pion until it was absorbed or until a certain amount of time had passed. In this model I tried to use the best characteristics of the $\bar{p}$ INCs done before by Clover et al.[17] and Cahay et al.[18]. I first created a pion-nucleus code and compared the results with the large body of relevant pion-nucleus data available from LAMPF[19] to verify that the models used to include Pauli blocking, true pion absorption, Fermi motion etc., were correct and to fix the parameters in these models. In this way it was insured that pions were being propagated and absorbed in a realistic manner.

Densities were calculated in two ways: by counting the number of nucleons in spacial bins (averaged over a large number of realizations of the annihilations) and by using a 4th nearest neighbor estimator. The two densities so obtained agreed with each other and gave a maximum density of 1.4-1.6 ρ_o in substantial agreement with the hydrodynamic calculation.

The nucleon temperature was obtained by binning the nucleon kinetic energies and using the slope of the observed exponential distribution. Note that these temperatures do not include the energy density due to the presence of unabsorbed pions.

Figure 4 shows the temperatures obtained under different conditions with the two different calculations. The temperatures reached for the largest energy depositions considered clearly reach the hoped-for values of ~180 MeV. While it is clear that the calculations don't exactly agree (why should they?), it is likely that the truth is to be found somewhere between them and the temperature accordingly.

The first results from LEAR[20] (as well as some old experiments) which can be compared with our low energy calculations are roughly in agreement and would say, if anything, we are too conservative in the temperatures achieved in the present calculations.

We note also, as can be seen from the plot, that we have an extra cushion in that $\bar{d}$ beams of reasonable intensity can be obtained and that these are even more efficient at depositing energy in the nucleus than $\bar{p}$ beams.

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